



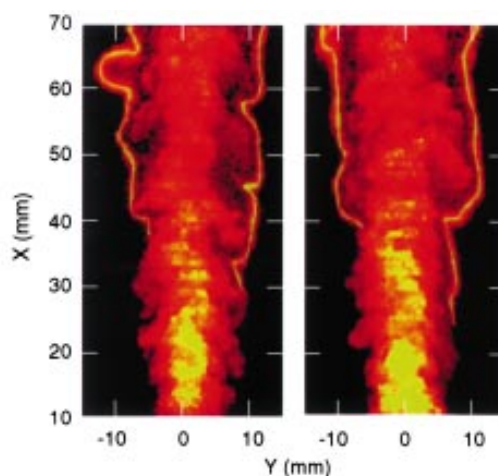
Turbulent flame stabilization mechanisms studied

Robert Schefer, in collaboration with Mehdi Namazian from Altex Technologies Corporation, has developed a double-pulse, planar imaging technique to study the temporal development of interactions between turbulence and flame chemistry. Ignition, extinction and flame propagation in turbulent reacting flows are the result of local interactions between fluid motion and flame chemistry and are important factors controlling flame stability. The mechanism whereby these factors control stability is, however, not well understood. Temporally-resolved imaging techniques are uniquely suited to help us better understand these inherently unsteady phenomena.

Under sponsorship of the DOE Office of Basic Energy Sciences and the Gas Research Institute, which funded the Altex portion of this work, Bob and Mehdi modified the Combustion Research Facility's flash-lamp-pumped dye laser Diana to provide two laser pulses with a variable time delay between pulses. The laser was reconfigured into two separate lasers consisting of one oscillator and amplifier stage each. The beams were formed into overlapping sheets in a multipass cell and were tuned to a wavelength of 431.5 nm, which was used to detect methane molecules by Raman scattering and to simultaneously induce fluorescence in CH. The combined CH fluorescence and CH₄ Raman-scattering signals from the two laser shots were detected using two intensified CCD cameras located on opposite sides of the laser sheet.

An example of the interactions observed between fluid motion and the flame is seen from the combined


CH/CH₄ images in Fig. 1. These images were obtained in a lifted, methane-jet flame at a jet Reynolds number of 7,000. The image to the left was taken during the first laser shot, 2 msec before the image to the right. The high CH concentration region, used to define the flame zone, appears as two bright bands along the outside of the fuel jet, which is indicated by the broader, colored region. Note that the high CH concentration regions begin several millimeters downstream of the image bottom where the flame is stabilized.



Double-pulse images of the instantaneous CH/CH₄ distribution in a turbulent, lifted CH₄-jet flame. The color scale is linear with higher concentrations indicated by lighter shades. The flow is from bottom to top with the fuel jet exit located 10 mm below the bottom of the images. The time delay between the left and right image is 2 msec. Vortical structures in the region of the flame zone would travel a maximum of 20 mm during this 2 msec delay.

The interaction of a vortical structure with the flame can be observed in

the left image where an outward bulge in the flame zone has begun to form along the left edge of the jet at an axial location of $x=40$ mm. The right image, taken 2 msec later, shows further development of the structure. In the latter image no CH exists upstream of the structure. This behavior is consistent with extinction of the flame along the upstream edge of the vortical structure due to rapid entrainment of air. In this case, insufficient residence time is available for mixing between entrained air and fuel from the central jet, and flame extinction occurs. Along the right side of the jet the development of a vortical structure near the center of the image is again apparent. In this case, however, the flame is not extinguished at the structure's leading edge indicating mixing rates at the upstream edge of the structure are lower and the residence time is sufficient to maintain combustion.

These results illustrate the interactions that occur between vortical structures and the flame. Further analysis of the images shows that flame stabilization is determined by a balance between flame extinction and upstream premixed flame propagation. The double pulse imaging data clearly establishes the importance of unsteady interactions between turbulence and the flame and suggests that computational models for turbulent combustion must account for such interactions if flame stability is to be predicted. Future experiments will extend this technique to include determining the instantaneous velocity field using planar imaging velocimetry. The additional velocity field data will help quantify the local strain rates. 

In situ surface chemistry and emissivity diagnostic developed

Larry Baxter, assisted by Gian Sclipa, has developed techniques in the CRF's Multifuel Combustor (MFC) for *in situ* monitoring of the species composition and emissivity of surfaces in combustion environments. The technique has been applied to ongoing investigations of ash deposits formed from inorganic materials during combustion of most solid and many liquid fuels. The utility of the diagnostic is illustrated in its recent application to a specific problem in coal-fired utility boilers done in collaboration with John Harb and Galen Richards (Brigham Young University).

The conceptual design of the diagnostic is easy to understand. Infrared thermal emission from a surface is spectrally resolved to determine a spectral emissivity. The spectral features of the emissivity identify chemical species on the surface.

The complexities are several: distinguishing radiative emission from the relatively cool (300 - 800°C) boiler surface from radiative reflections from the hotter (900 - 1700°C) gases and soot-laden flame; dealing with interferences from both hot combustion gases and cool atmospheric gases that are infrared active; analyzing signals that include components from the surface and the turbulent, particle-laden, reacting flow; and interpreting spectral data from inhomogeneous, porous deposits with large temperature gradients. Current results establish confidence in the qualitative and semi-quantitative interpretation of chemical species information and quantitative emissivity information.


In the collaboration with BYU, two low-sulfur western US coals of similar organic and inorganic elemental compositions were tested in utility-scale boilers. By all traditional analyses, these coals should have behaved similarly; however, field experience indicates that one coal is more problematic in terms of managing the ash deposits.

To find the underlying reasons for the difference, the two coals were tested in the MFC under identical operating conditions. The composition of ash deposits accumulating on temperature-regulated probes was monitored

using the new diagnostic.

Figure 1 illustrates the differences in the deposit composition. While both deposits are composed of mixtures of silica, various silicates, and several sulfates, the relative intensities of the emission features associated with these species differ.

These *in situ* data were complemented by *ex situ* data of several types. One example is cross section images of the same deposits, generated by Galen using a scanning electron microscope (SEM). The elemental compositions of the deposit cross sections (Fig. 2) confirm the chemistry indicated by the spectroscopy data in Fig. 1.

The diagnostic is also applicable to corrosion and heat transfer analyses in coal-, biomass-, and waste-fired boilers. Future applications of the technique include studies of high-temperature corrosion of metal surfaces in combustors; corrosion of silicon carbide in high-temperature, oxidizing, alkali-laden combustion gases; and determination of the effects of low- NO_x burners on deposit chemistry. 

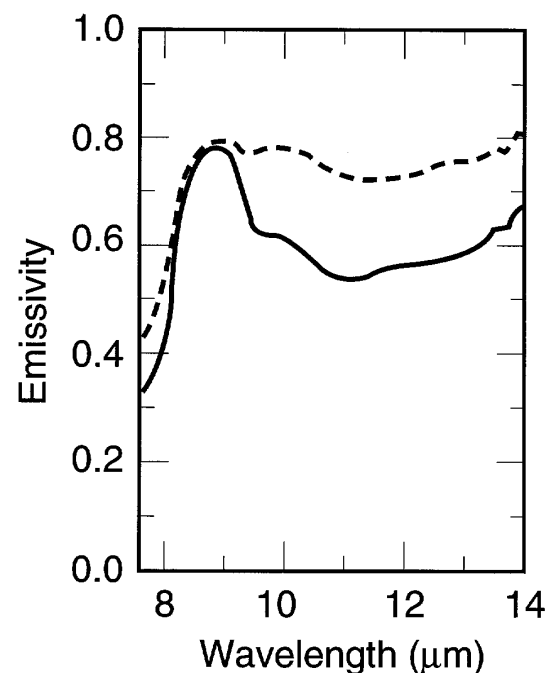


Figure 1. Spectral emissivities collected *in situ* in the MFC for two similar low-sulfur coals. Emission intensity from sulfates (near 8.8 μm) and silica (near 9 μm) differs from that of many of the silicates (10 to 13.5 μm) by a large ratio for one coal (solid line) but by a much smaller ratio for the second (dashed line).

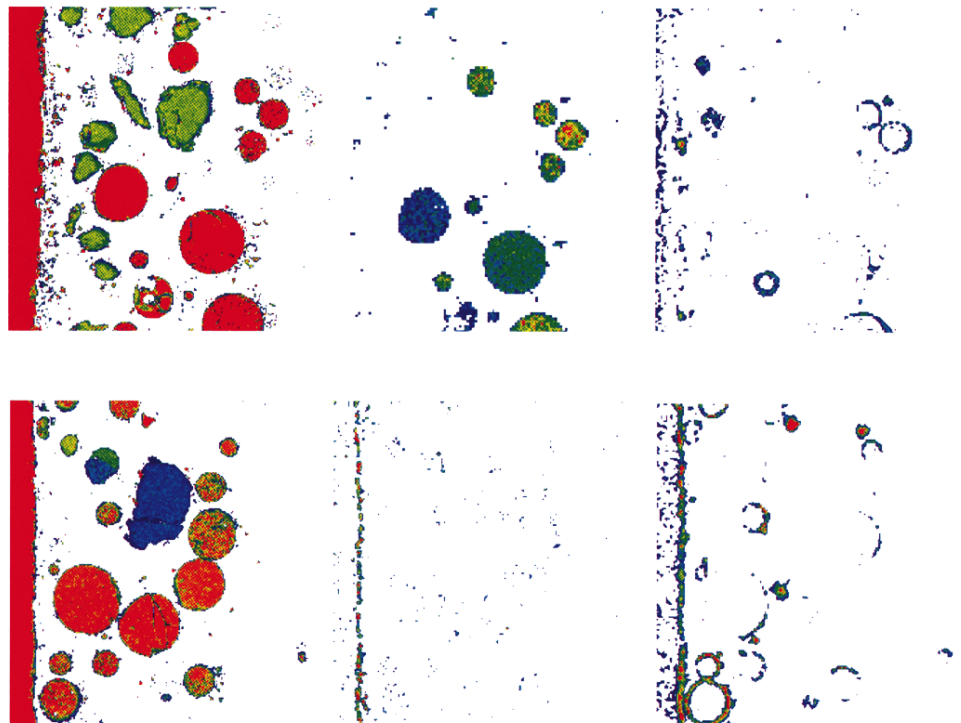
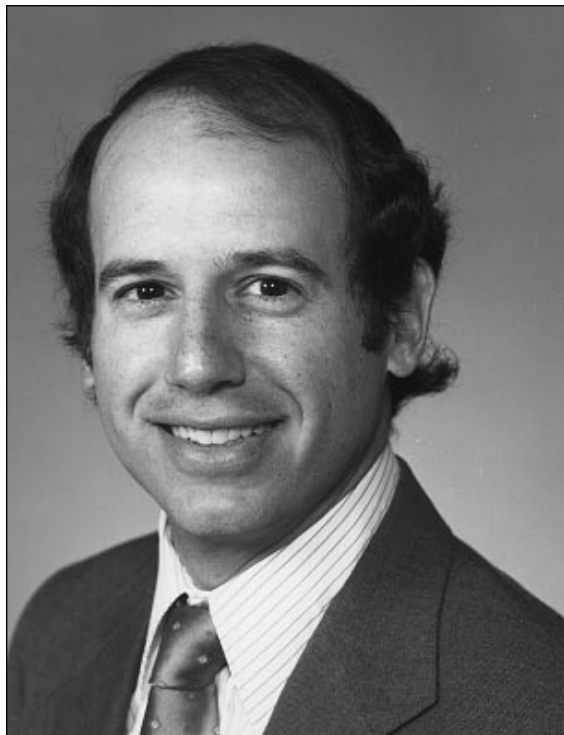


Figure 2. SEM image of cross-section of deposits formed on a probe in the MFC. The probe surface is seen on the left of each image. The top row shows data from one coal illustrating overall deposit structure (left), calcium map (center), and sulfur map (right). The bottom image illustrates similar results from the second coal, with the center section representing a sodium map rather than calcium. Formation of sulfates on the surface of the probe and CaO particles is evident.



John Goldsmith was recently appointed a Fellow of the Optical Society of America. The citation accompanying his award noted "... his pioneering contributions to laser spectroscopy, remote sensing, and combustion diagnostics, most notably his novel techniques for detecting radicals in flames" (*Optics & Photonics News*/September 1994).

John's thesis work at Stanford University concentrated on high-resolution atomic spectroscopy. After obtaining a Ph.D. in physics in 1979, he continued working on atomic spectroscopy for a year as a post-doctoral research associate at the Joint Institute for Laboratory Astrophysics. John joined Sandia in 1980, developing new techniques for laser-based combustion diagnostics for ten years, followed by a shift into his current work developing laser remote sensing techniques for atmospheric studies.

John has been very active in the Optical Society of America, serving the full range of program responsibilities (committee member, program chair, and general chair) for two OSA conferences, the topical meeting on *Laser Applications to Chemical Analysis*, and *CLEO* (Conference on Lasers and Electro-Optics), for which he is currently General Co-Chair.

Sandia National Laboratories, a prime contractor to the U.S. Department of Energy, is operated by Sandia Corporation, a wholly owned subsidiary of the Martin Marietta Corporation.



Visitors Ruth McKay (left), working with Professor Richard N. Zare of Stanford, and Steve Wilson (center), working with Professor Michael Ashfold of the University of Bristol, visited David Chandler (right) to work on photofragment imaging experiments this summer. Ruth has now taken a position in Dr. Paul Houston's laboratory at Cornell and Steve has returned to England to construct an apparatus similar to the one he worked on in Dave's laboratory.



Volker Sick (left), Institute of Physical Chemistry, Heidelberg University, has been working with host Roger Farrow (right) and Phil Paul (not shown). Volker's interests are degenerate four-wave mixing and planar laser-induced fluorescence techniques for combustion diagnostics.

Reaction product imaging: the H + D₂ reaction

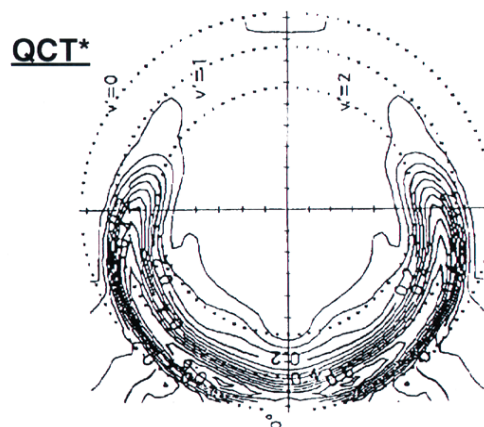
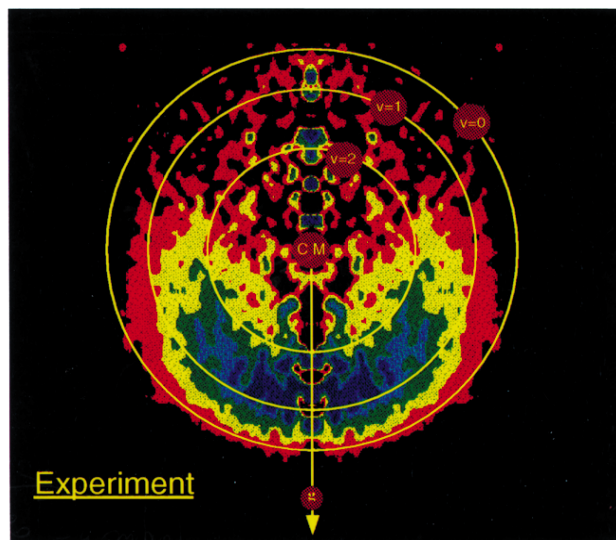
Dave Chandler, in collaboration with David Baldwin (Ames Laboratory, Iowa) and Theo Kitsopoulos (University of Crete) and visitors Mark Buntine and Dick Zare from Stanford University, has developed a new technique called Reaction Product Imaging for the study of differential cross sections of bimolecular reactions. In an initial study the differential cross section for the H + D₂ → HD + D reaction was measured.

In the experiment, a photolytically produced beam of H atoms crosses a beam of cold D₂ molecules. At the intersection the reagents form D + HD in various translational/internal-excitation combinations. The velocity of the D atom reflects the internal state of the HD product formed in coincidence. The product D-atoms are photoionized and accelerated toward a position-sensitive detector.

The ion images appearing on the detector are two-dimensional projections of the three-dimensional velocity distribution of the D-atom products. The investigators studied the reaction at nominal center-of-mass collision energies of 0.54 eV and 1.29 eV. At the lower collision energy, the measured differential cross section for D-atom production, summed over all final states of the HD(v, J) product, agrees well with recent quasi-classical trajectory calculations of Aoiz *et al.*, while at the higher collision energy the agreement between the theoretical predictions and experimental results requires the addition of geometric phase considerations to the calculation. Theory and experiment for the 1.29 eV collision energy are shown in the accompanying figure.

Ion images of atomic products are extremely useful in providing the overall appearance of the differential cross section for a reaction or photofragmentation process, since they contain information concerning all product channels. The information is sufficiently detailed to test the best potential energy surfaces and scattering calculations. This technique is being further developed and applied to the study of reactions of small hydrocarbons at Sandia and will be available to outside users through the CRF's Visiting Researcher Program. 📧

$E_{\text{CM}} = 1.29 \text{ eV}$



* F.J. Aoiz *et al.* Chem. Phys. Lett. 198, 321 (1992)

Experimentally measured (top) and theoretically calculated (bottom) velocity distributions of D atoms from the H + D₂ reaction. The rings superimposed upon the images reflect the speed the D atoms would be traveling if the HD molecules formed in coincidence were in the lowest rotational state of the marked vibrational level and are concentric around the center of mass (CM).